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FIRST MID-INFRARED SPECTRUM OF A FAINT HIGH-Z GALAXY: OBSERVATIONS OF CFRS 14.1157 WITH THE INFRARED SPECTROGRAPH[1] ON THE SPITZER SPACE TELESCOPE [2]

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ABSTRACT

The unprecedented sensitivity of the Infrared Spectrograph on the Spitzer Space Telescope allows for the first time the measurement of mid-infrared spectra from 14 μm to 38 μm of faint high-z galaxies. This unique capability is demonstrated with observations of sources having 16 μm fluxes of 3.6 mJy (CFRS 14.1157) and 0.35 mJy (CFRS 14.9025). A spectral-fitting technique is illustrated which determines the redshift by fitting emission and absorption features characteristic of nearby galaxies to the spectrum of an unknown source. For CFRS 14.1157, the measured redshift is z = 1.00 $\pm$ 0.20 in agreement with the published result of z = 1.15. The spectrum is dominated by emission from an AGN, similar to the nucleus of NGC 1068, rather than a typical starburst with strong PAH emission like M82. Such spectra will be crucial in characterizing the nature of newly discovered distant galaxies, which are too faint for optical follow-up.

Subject headings: dust, extinction — galaxies: high-redshift – galaxies: individual(CFRS 14.1157, CFRS 14.9025, CFRS 14.1129) infrared: galaxies — galaxies: AGN — galaxies: starburst

1. INTRODUCTION

Observational studies of the star formation history of the universe indicate that the star formation density rises rapidly from the present to z $\sim$ 1 with very uncertain behavior at higher redshifts (e.g., Elbaz & Cesarsky 2003 and references therein). Determining the luminosity functions and redshift distribution of dusty starburst galaxies is crucial to deducing the star formation history of the universe. The infrared and submillimeter windows are ideal hunting grounds for discovering these sources as most of the luminosity from starbursts is re-radiated by dust at infrared and submillimeter wavelengths. A closely related problem is discriminating between starbursts and AGNs as the fundamental power source for heating this dust.

The Infrared Space Observatory (ISO) detected such infrared galaxies down to $\sim$ 0.1 mJy at $\sim$15 μm within some small survey areas, such as the Canada-France Redshift Survey (CFRS) fields number 1415+52 and 0300+00 (Flores et al. 1999) and the Hubble Deep Field North (HDFN) (Aussel et al. 1999). The redshift distribution of the ISO sources peak at z $\sim$ 1. These results are used to infer the evolution of star formation under the assumption that these galaxies are primarily powered by starbursts. In some cases, this assumption can be confirmed by optical emission line ratios, but in many cases - especially the most luminous sources - the optical spectra show indicators of AGN (Veilleux et al. 1999), so it cannot be determined what fraction of the infrared luminosity derives from a starburst compared to the fraction from the AGN.

If z > 1 galaxies are similar to those in the local universe we would expect starbursts to have strong polycyclic-aromatic hydrocarbon features (PAH, at rest wavelengths 6.2 μm, 7.7 μm, and 11.3 μm). These are thought to arise in photodissociation regions around hot stars and are so common in starbursts that they are used as a starburst vs AGN spectral classifier, as the PAHs are easily destroyed by the harder radiation field from an AGN accretion disk (e.g., Genzel et al. (1998); Lutz et al. (1998)). Laurent et al. (2000) extend this scheme to three templates (AGN, PDR and HII) to discriminate between a pure AGN component, quiescent star forming regions with strong PAHs associated with the PDR component and a starburst component with weak PAH emission (i.e HII-like emission). The mid-infrared (MIR) continuum can also have a silicate absorption feature (rest wavelength $\sim$ 9.7 μm) from an embedded AGN within an optically thick torus, or from optically thick dust cocoons around hot stars. An embedded source is also likely to have ice and gas absorption features (e.g., Spoon et al. this issue). PAH and silicate features as strong as those in many nearby galaxies would allow determination of redshifts to z $\sim$ 3 for galaxies as faint as $\sim$ 1 mJy at 16 μm using the low resolution modules of the Infrared Spectrograph on Spitzer (Houck et al. this issue). At z $\gtrsim$ 1 these objects are likely to be be ultraluminous infrared galaxies (ULIRG) with $L_{IR} \sim 10^{12} L_{\odot}$and hyper-luminous infrared galaxies (HLIRG) with $L_{IR} \gtrsim 10^{13} L_{\odot}$. If these objects are similar to those found in the local universe we may expect to find a dominent AGN in sources with $L_{IR} \gtrsim 10^{12.4} L_{\odot}$(Tran et al. 2001).

It is anticipated that many important discoveries from Spitzer will derive from wide area surveys, which will re-

[1] The IRS was a collaborative venture between Cornell University and Ball Aerospace Corporation funded by NASA through the Jet Propulsion Laboratory and the Ames Research Center.
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veal large numbers of infrared galaxies that are too faint for optical follow-up. Hence, the capability to measure faint mid-infrared (MIR) spectra is crucial.

Observations of CFRS 14.1157 were taken as a first test of the IRS long-wavelength low resolution spectrograph's (IRS-LL) ability to measure the redshift of faint z > 1 galaxies using MIR spectral features and to characterise the MIR luminosity. The serendipitous observation of CFRS 14.9025, a galaxy at z = 0.155 having flux only 0.35 mJy at 16 μm, further demonstrates the ability of the IRS to observe faint sources.

CFRS 14.1157 is a galaxy identified with the radio source 15V23 (Fomalont et. al. 1991). The source is at a z of 1.15 (Hammer et. al. 1995), which corresponds to a luminosity distance of 7900 Mpc ($H_o = 71$ kms^{-1}Mpc^{-1}, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, $\Omega_k = 0$) and an angular scale of 8 kpc per arcsecond. The source was detected by ISO-CAM with a 15 μm flux of 2.3 $\pm$ 0.08 mJy (Flores et al. 1999). However, the source appears extended and revised photometry indicate that its flux is 3.1 $\pm$ 0.3 mJy (Flores private communication). The HST I band image shows a multi-component source embedded in diffuse emission and extended over a region of $\sim$ 2.5 " (20 kpc) (Webb et al. 2003). Waskett et. al. (2003) detected x-ray emission with XMM-Newton and inferred the presence of a fairly heavily obscured AGN from the 0.5-2/2-10 keV band hardness ratio of $\sim$ -0.3. However, a comparison between the observed submm flux and that predicted from the AGN led Waskett et. al. (2003) to conclude that there is a strong starburst component present.

The empirical limits which can be reached by the IRS in searching for spectral features in faint sources and techniques for optimal spectral extraction and template fitting using the SMART analysis package (Higdon et al. 2004) are described in Section 2. The results and the nature of CFRS 14.1157 are discussed in Section 3. The conclusions are presented in Section 4.

2. OBSERVATIONS AND ANALYSIS

The IRS-LL module provides low resolution spectra (resolving power, $64 \leq \frac{\lambda}{\Delta\lambda} \leq 128$) between 14.0 μm and 21.3 μm in long-low 2 (IRS-LL2) and 19.5 μm - 38.0 μm in long-low 1 (IRS-LL1). The observation was made on the 5^{th} of January 2004 in the IRS Staring Mode AOR, which integrated for 6 $\times$ 120 seconds at each of the two nominal nod positions on each of the two slits (for observing mode details see chapter 7 of the Spitzer Observers Manual (SOM)[7]). Therefore, the total integration time required to obtain the entire spectrum shown in Figure 1 was 2880 seconds.

In order to accurately place the source on the slit, CFRS 14.1157 was first observed in the IRS blue peak-up camera. This also gives an independent measure of the flux at 16 μm. The peak up images revealed two serendipitous detections of the galaxies CFRS 14.9025 and CFRS 14.1129. The slit orientation fortuitously included CFRS 14.9025, see Figure 2. The peakup photometry was based on the three double-correlated sampled images which were co-added on board and were obtained when the science target was in the sweetspoot location of the camera (see the SOM). CFRS 14.1157 has a blue peak-up 16 μm flux of 3.29 $\pm$ 0.66 mJy, which agrees

[7] `http://ssc.spitzer.caltech.edu/documents/som/`

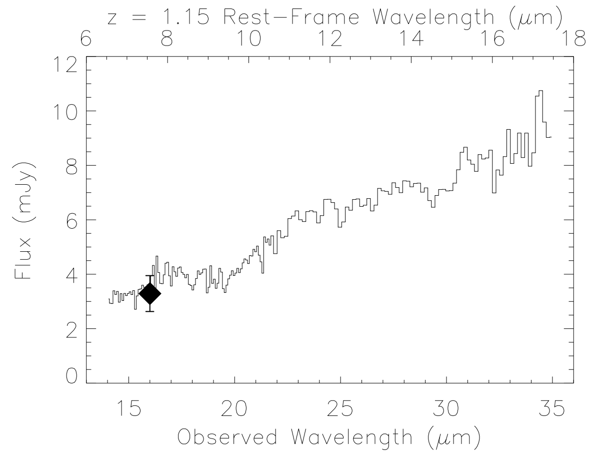

FIG. 1.— IRS-LL spectrum of CFRS 14.1157 (z = 1.15) with total integration time of 2880 seconds. The diamond symbol is the blue-peakup flux.

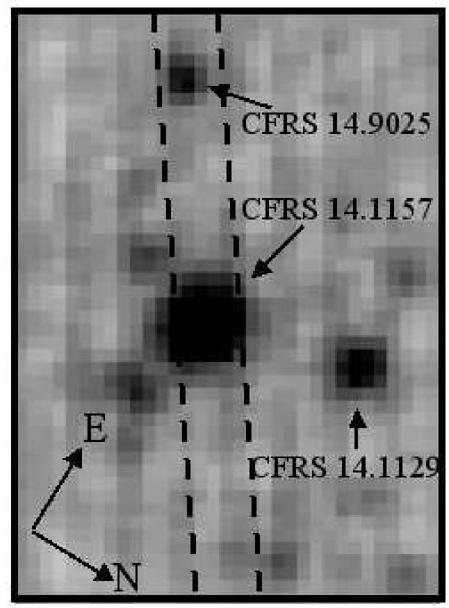

FIG. 2.— Image from the Blue Peak up Camera on the IRS, having field of view 60" by 72" and integration time 48 seconds. Dashed line is the LL slit position generated by the Spitzer Planning Observations Tool (SPOT).

with the revised ISOCAM 15 μm flux. The source positions and 16 μm fluxes are listed in Table 1. The spectral data were processed as far as the un-flatfielded two dimensional image using the standard IRS pipeline (see the SOM). The spectra were then extracted and sky subtracted using the SMART analysis package (for details see Higdon et al. 2004).

The extracted spectra were flat-fielded and flux-calibrated by extracting and sky subtracting un-flatfielded observations of the calibration star del UMi (from the same campaign) and dividing these data by a del Umi template (Cohen et al. 2003) to generate a 1-dimensional relative spectral response function (RSRF). The RSRF was then applied to the observations of CFRS 14.1157 and CFRS 14.9025 to produce the final spectra. The spectra of CFRS 14.1157 and CFRS 14.9025 are shown in Figures 1 and 3, respectively. Their 16

TABLE 1
CFRS Sources in IRS Blue Peakup

CFRS	RA[a] (J2000)	Dec[a] (J2000)	z [a]	$F_{16\mu m}$ [b] (mJy)
14.1157	14:17:41.80	52:28:24	1.149	3.29 ± 0.66
14.9025	14:17:44.99	52:28:03	0.155	0.38 ± 0.08
14.1129	14:17:42.60	52:28:46	0.831	0.66 ± 0.13

[a]http://www.astro.utoronto.ca/~lilly/CFRS/
[b]IRS Blue Peak up flux.

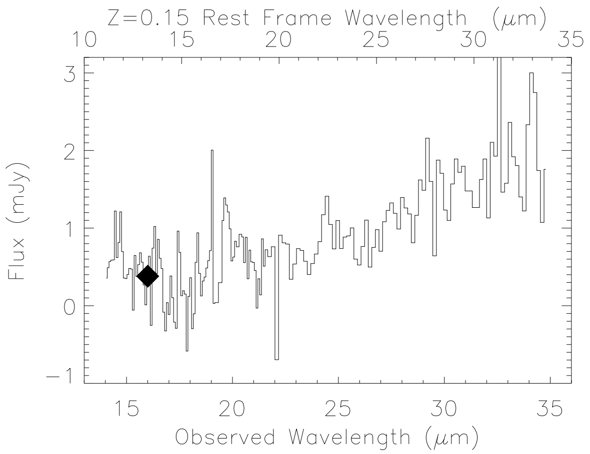

Fig. 3.— IRS-LL spectrum of CFRS 14.9025 (z = 0.155) with total integration time of 1440 seconds. The diamond symbol is the blue-peakup flux.

TABLE 2
IRS Low Resolution Spectral Characteristics

CFRS	$S/N_{16\mu m}$	$RMS_{16\mu m}$ [a] (mJy)	$S/N_{26\mu m}$	$RMS_{26\mu m}$ [a] (mJy)
14.1157	12	0.31	26	0.25
14.9025	1	0.35	4	0.19

[a]RMS noise calculated from 0-order polynomial fit to the continuum between 15 and 17 μm and 25 and 27 μm, respectively.

μm fluxes are 3.6 mJy and 0.35 mJy, respectively, which matches the peak-up fluxes to 15 %. The integration time for CFRS 14.9025 is only half that for CFRS 14.1157 because the former object was present only in one of the two nod positions. In the observation of CFRS 14.1157 the 16μm rms noise is 0.31 mJy and the 26 μm rms is 0.25 mJy. In CFRS 14.9025 the noise is similar but the S/N is lower (see Table 2).

The redshift was determined using a simple template fitting algorithm in which infrared spectra of starburst galaxies or AGN were first redshifted over the interval 0<z<3 in steps of 0.04, regridded, scaled, and then compared to the IRS source spectra. Only discrete emission and absorption features are fitted, hence the shape of the continuum is treated as a free parameter. The value of z that minimized the reduced χ^2, defined as

$$\chi^2_{\rm z} = {\rm N}_{\rm free}^{-1} \;\; \Sigma\, \sigma^{-2} \; (\; {\rm D}_\lambda - {\rm a}(\; {\rm T}_{(1+{\rm z})\lambda} \; + \; {\rm b}_\lambda \;)^2 \qquad (1)$$

was taken to be the source's redshift. In this equation, D_λ and $T_{(1+z)\lambda}$ are the input IRS source and redshifted template spectra, respectively. Scaling of the template spectrum is managed by the constants a and b_λ. The uncertainty in z is estimated by numerically calculating

$$\sigma^2_{\rm z} = \frac{2}{\partial^2 \chi^2_{\rm z} / \partial {\rm z}^2}. \qquad (2)$$

Because the CFRS spectra were obtained only in the second IRS campaign, a sufficient number of sources have not yet been observed with the IRS to produce a detailed catalog of starburst and AGN templates. For this paper the templates are the ISO-SWS spectra of M 82 and NGC 1068 (Sturm et al. 2000) convolved to the IRS-LL resolution.

TABLE 3
Relative 7.7 μm and 11.3 μm PAH Strengths

	Relative Flux[a] 7.7 μm PAH	RelativeFlux[a] 11.3 μm PAH
CFRS14.1157	$\leq$0.3[b]	$\leq$0.1[b]
M82	7.2[c]	1.2[c]
NGC1068	0.1[c]	0.06[c]

[a]PAH flux/continuum (11.6 - 11.9 μm). Note that the fluxes are in units of Wcm^{-2}.
[b]The upper limit: 3-$\sigma\times$ observed bandwidth.
[c]Sturm et. al. 2000.

3. RESULTS

The CFRS 14.1157 MIR spectrum is featureless apart from a broad absorption dip at $\sim$ 19 μm (see Figure 1). There is no measurable PAH emission. The spectrum of CFRS 14.9025 is also featureless, but since the source is $\sim$ 8 times fainter than CFRS 14.1125 the signal to noise is low, meaning that if present, relatively strong PAH emission features could be buried in the noise (see Table 3).

Using the spectral template method described in the previous section and an AGN template, the minimal-χ^2_z redshift is 1.00 ± 0.20 for CFRS 14.1157 (see Figure 4). The fit identifies the broad absorption feature at $\lambda \sim 19$ μm with silicate absorption at $\sim$ 9.7 μm, seen in NGC 1068. This is consistent with the optically derived redshift of z = 1.15 ± 0.05 (Hammer et al. 1995). In Figure 5 the observed spectrum is shown overlayed with scaled versions of the M82 and NGC 1068 templates redshifted to z = 1.0. The absence of strong PAH features reveals that a typical starburst spectrum is inconsistent with the observation of CFRS 14.1157. Moreover, the continuum shape is clearly AGN like.

To estimate a formal limit to the relative 7.7 μm and 11.3 μm PAH strength, the bandwidths for the PAHs are defined as 7.3 to 8.2 μm and 11.1 to 11.7 μm, respectively. A zero-order polynomial fit to the continuum over the corresponding PAH band is fitted and the rms is calculated. The integrated continuum between 11.6 and 11.9 μm is measured. This is an "off band" region where no known spectral features are found. The limit is then defined as three times the rms multiplied by the PAH bandwidth and divided by the "off band" flux. As shown in Table 3, 7.7 μm (11.3 μm) PAH emission relative to the continuum, must be at least 24 (12) times

FIG. 4.— Reduced χ^2 for redshift determination of CFRS 14.1157 using NGC 1068 as a template.

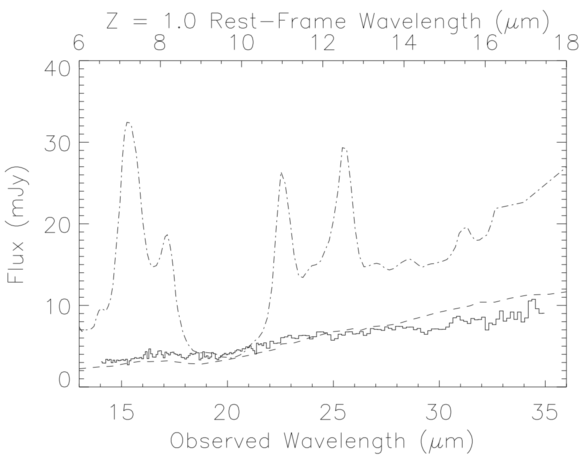

FIG. 5.— CFRS 14.1157 overlaid with M82 (dot-dash line) and NGC 1068 (dash line) templates at a redshift z = 1.0, determined by the MIR fit.

fainter than observed in M82. In nearby galaxies the flux at 15 μm is strongly correlated with the infrared luminosity, with $L_{IR} \sim 11.1\ L_{15\mu m}$ (Chary & Elbaz 2001). If this correlation holds for more distant galaxies, then the IR luminosity of CFRS 14.1157 is $\sim 10^{13}\ L_\odot$, i.e. it is a hyper-luminous infrared galaxy.

The observed spectrum of CFRS14.9025 is featureless and its redshift could not be determined using the IRS. At a luminosity distance of 731.4 Mpc the infrared luminosity, extrapolated from the 15 μm flux, is 6×10^9 $L_\odot$. Assuming that there is no AGN contribution to the IR luminosity, this would correspond to a star formation rate of $\sim 1\ M_\odot\ yr^{-1}$, using SFR $[M_\odot\ yr^{-1}] = 1.72 \times 10^{-10}\ L_{IR}[L_\odot]$ (Kennicutt 1998).

4. CONCLUSIONS

We have demonstrated the ability of the IRS-LL to determine the redshift of a faint galaxy with $f_{16\mu m} = 3.6$ mJy. An rms of 0.3 mJy is reached with 2880 seconds of integration. The observations indicate that CFRS 14.1157 is dominated by emission from an AGN component in the MIR and belongs to the hyperluminous class of infrared galaxies.

The serendipitous observation of CFRS 14.9025 demonstrates that we can obtain a low resolution spectrum of a source at a flux level of 0.35 mJy at 16 μm. The IRS low resolution MIR capability will be crucial in characterizing the nature and luminosity of newly discovered galaxies at high redshift.

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